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Design Evaluation of the Cold Precision Forging die for Part of Straight Bevel Gear by Simulation and Experiment

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Abstract— *Straight bevel gears are an important part of mechanical transmissions. To ensure product quality and high productivity, this part is often bulk forming instead of cutting. The commonly used method to manufacture gears is hot forging. However, the disadvantages of this method are low surface quality, low precision, additional heating step, post-forging treatment, and not significantly improving the mechanical properties of the product after stamping. Therefore, the cold forging method is considered as an alternative to overcome the above disadvantages. To be able to use this method, the important point is that the die design must be suitable for the workpiece material, the degree of deformation of the part to ensure the ability to fill the die cavity and the life of the die. This study presents a typical cold forging die design process for forming parts of a straight bevel gear from A5053 aluminum material. The design is evaluated by simulation and verified through experiment. The simulation also allows determining important parameters such as material flow, effective strain, effective stress, breaking capacity, stamping force to evaluate the possibility of scrap and optimize the design.*

Keywords— *Precision die forging, Closed die, FEM, Straight bevel gear.*

I. INTRODUCTION

Cold forging is one of the methods of metal forming by pressure. The workpiece is formed at room temperature, and this method requires high force, hardening material, and low plastic deformation capacity. However, it has several advantages that hot and/or warm forging cannot have, which is to produce high-quality parts in relation to surface quality, dimensions, save materials, improve mechanical properties through deformation, reduce the number of operations [1]. Many parts are manufactured by cold forging applied in fields such as automobile, aerospace, marine, railway, etc., such as gears, crankshafts, couplings, etc. In cold forging, the step of die design to ensure that the product is manufactured with the required quality and the required durability is very important for the manufacturer. In addition, shortening the testing time, optimizing mold design to quickly bring products to market, is also an urgent requirement today. The numerical simulation method combined with experiments has also been studied and applied to solve this problem [2].

In order to gain a deeper understanding of the cold precision forging die design step, this study introduced the process of designing a die for a straight bevel gear from A5052 Aluminum. In this study, numerical simulation tools are also used to further analyze the destructive capacity of materials, stress, deformation, metal flow, ability to fill the mold cavity as well as determine the stamping force, thereby evaluating the reasonableness of the proposed mold design. An experimental system is also built to test forging and evaluate the quality of stamping products.

II. MATERIALS AND METHODS

A. Cold Forging Part

The part selected for this study is a straight bevel gear with the material and specifications of the gear given in Table 1 and 2. The bevel gear is a gear that rotates between two axes intersect. The bevel gear is an indispensable part of a vehicle's operating system or an industrial machinery system.

B. Die Design Process

1. Determine the original workpiece

From the part volume, adding the machining allowance will determine the original workpiece volume. Based on this volume to give the appropriate shape and size of the workpiece (Figure 1).

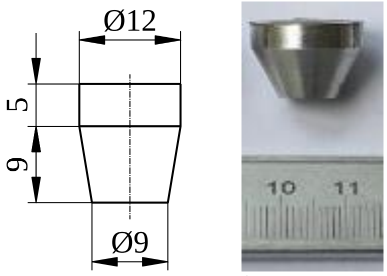

Fig. 1. Shape and size of workpiece

2. Parting plane

The parting plane is responsible for dividing the forging die into the upper and lower die. The basic condition for selecting the parting plane is that it must be easy to remove the stamping material from the die cavity; favorable for filling the die cavity; produce the right grain direction of the metal [4]. The parting plane is selected (in Figure 2) to ensure that the above criteria are met.

3. Die angle

In the production process, to increase production capacity and ensure the quality of stamping products, it is required that

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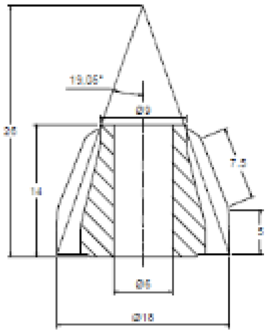
when stamping, the metal must be filled with the mold cavity, and moving the stamping object out of the mold cavity is easy.

TABLE 1. Mechanical properties of workpiece [3]

Alloy	Temperature (ºC)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Young's modulus (GPa)	Poisson's ratio	Density (kg/m$^{3)}$
A5052	24	90	193	25	70	0.35	2680

TABLE 2. Straight bevel gear specifications

	Parameters	**Symbol/unit**	**Value**
	Module	m	2.25
	Number of teeth	z	9
	Pitch Angle	δ (^{0})	19.5
	Teeth face width	B (mm)	7.5
	Pitch diameter	D_p (mm)	18
	Outside diameter	D_{max} (mm)	18
	Bore diameter	d (mm)	6

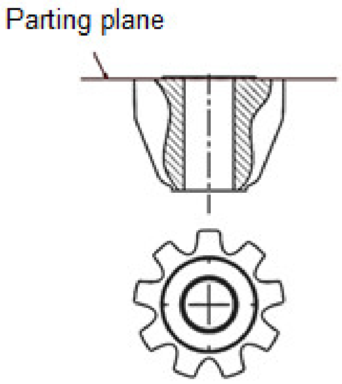


Fig. 2. Parting plane

To achieve that, the inclination angle of the die cavity wall must be consistent with the detail [5].

In this study, the stamped part is a straight bevel gear that already has an inclination angle; with the selection of the parting plane as above, we do not need to calculate the inclined angle of the cavity wall of the forging die.

4. *Punch – die*

The punch and the die are two parts that work directly with the workpiece, have the characteristics of working with high forging force, and require high surface quality in the mold cavity along with high strength and high pressure resistance [6]. From that requirement, the material for making punches and stamping dies is SKD61 (JIS), heat treated to reach hardness 55-58 HRC. The surface of the mold cavity is required to reach the technical roughness value Ra = 0.63. Based on the product profile and to facilitate the metal to flow into the pins of the gear, the punch and the die have been designed as shown in Fig 3.

5. *Stress ring of punch and stress ring of die (s)*

Due to the use of precision cold stamping in a closed die, the pressure exerted on the tool is very high, especially at the end of the forming process, so in addition to using materials with good mechanical properties to manufacture punch and die, we need to design Stress ring of punch and stress ring of die (s), both to help position and act as a stress ring, creating prestress to increase the life of punch and die as well as reduce costs. materials and manufacturing costs [7].

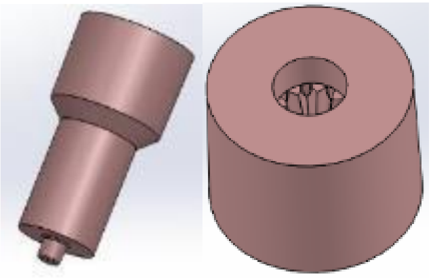


Fig. 3. Work-piece and tool models used in FEM simulation

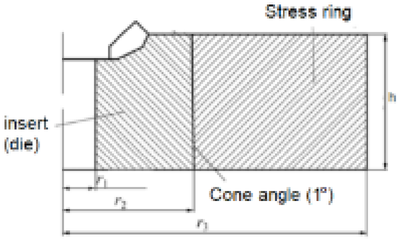


Fig. 4. Die Structure

The radius of the outer ring of the die is selected according to the formula [8]:

$$r_3 = (2 - 3)\, r_2 \qquad (1)$$

$$r_2 = (3 - 4)\, r_1 \qquad (2)$$

$$h >= r_2 \qquad (3)$$

6. *Calculation of stamping force and selection of equipment for the stamping process*

The determination of the stamping force allows the selection of suitable equipment. In this case, we can also calculate the required technological force similar to the method of metal backflow pressing in the cold state according to the formula [9]:

$$P = F.\, q \qquad (4)$$

with:

P – Force

F – The area of the punch tip on the surface perpendicular to the press axis; mm

q – Pressure to press flow

This is a cold stamping operation in a closed die, the metal fills the cavity of the die according to the principle of extrusion, so the hydraulic press is selected for this cold stamping process thanks to the advantage of being able to adjust the stroke. punch, pressing speed as well as pressing force. The 125 ton hydraulic press was selected for the experiment on the basis of the available equipment of LAB.

TABLE 3. Process parameters of cold forging processes of the straight bevel gear.

Parameters	Value/Grade
Material of workpiece	AA5052
Temperature of work-piece (℃)	24
Material of dies	SKD61
Friction factor	0.08
Feed speed of punch (mm /s)	10
Compression stroke (mm)	10.8

C. *Numerical Simulation*

Numerical simulation of the cold stamping process was performed using deform-3D simulation software with the main process parameters listed in Table 3.

The simulation results will allow to determine die filling capacity, stress and strain distribution, forging force as well as possible defects on the product.

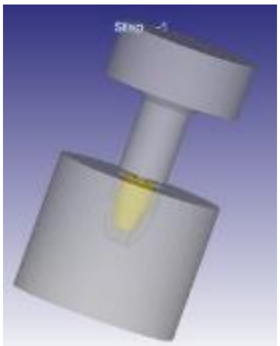


Fig. 5. Work-piece and tools used in FEM simulation

III. RESULTS AND DISCUSSIONS

A. *Simulation results*

1. *Metal flowing in Deformation Process*

The complicated shape of the driven straight bevel gear inevitably leads to complicated metal flowing, therefore the metal flowing should be investigated sufficiently. Figure 6, shows the filling processes in the hot and cold forging processes of the straight bevel gear with forging stages.

Fig. 6. Metal flowing in cold forging of the straight bevel gear

It can The Figure 7 shows the velocity vector of metal flow during the deformation process. Easily see that, the metal flow run more uniformly and stably during the hot forging process, be seen from Figure 6, in forging process of straight bevel gear, the filling processes of all gear-teeth are similar because of the rotational symmetry of the straight bevel gear.

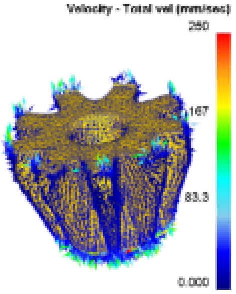


Fig. 7. Velocity in hot forging

2. *Effective strain and stress distribution*

The complicated metal flowing of the hot forging process of the driven straight bevel gear would lead to inhomogeneous plastic deformation. The effective strain distribution and evolution of forged straight bevel gear in hot and cold forging processes are shown in Figure 8 (left).

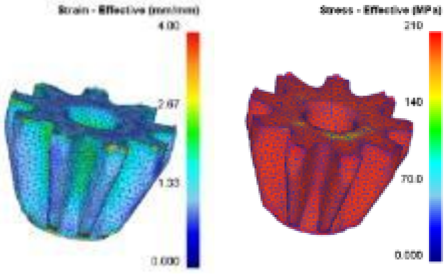


Fig. 8. Effective strain (left) and stress distribution (right)

Figure 8 (left) shows that with gear-tooth die feeding, the effective strain gradually accumulates on the workpiece. The effective strain on gear-teeth regions increases more obviously than that on other areas, which means that the plastic deformation mainly occurs on the gear-teeth. This is because that larger metal flowing resistance is caused by the complicated gear-teeth cavities, the plastic deformation is more severe on the gear-teeth regions. Secondly, the effective strain on the surface of each gear-tooth is larger than that inside the gear-tooth, which is attributed to the large friction resistance on the surface of each gear-tooth. Furthermore, the effective strain gradually increases from addendum to dedendum on each gear-tooth; this is because that the metal flowing is more intricate near the dedendum region because of the complicated die cavity.

Stress is a characteristic parameter for energy development process in forging technique. In deformation areas that have large strain impedance will occur high stress field. Stress field distribution on workpieces of the two different processes are shown in Figure 8 (right).

It can be seen that the stress distribution of the cold forging process is uniform, and the average stress is close to 175 MPa. By analyzing the effective stress distribution in the forging process, cold forging gives better micro-structure because the high pressure helps to refine the micro-structure in the gear part.

3. *Forming load and Scalar damage index*

The simulation forming loads of processes with increasing punch stroke are compared in Figure 9 (left). It can be seen that, the maximum forging load of cold forging process is 16.5 tons. In the early stages, the forging force is small due to the deformation of the workpiece according to the upset principle, the next stage the stamping force increases when the metal begins to flow into the teeth of the gear and the maximum forging force when the metal completely fills the cavity.

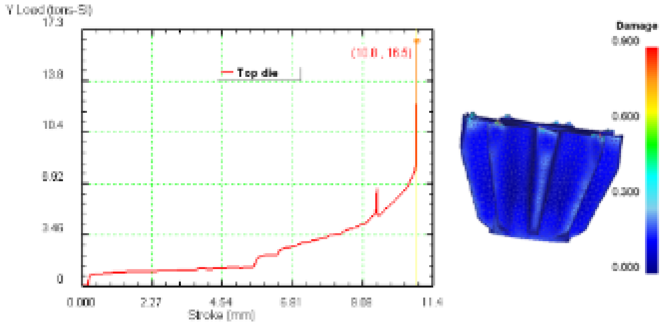


Fig. 9. Forging load curves of forging process (left) and Scalar damage index (right)

From the simulated product in Figure 9 (right), we get the results of evaluating the scalar damage index on the product; for any forged product, the scalar damage index is shown on the required part when the value is less than 1. The average scalar damage index of the cold forging simulation is much less than 1, so it can be concluded that the product is formed successfully in the cold stamping process, without any defects after the forming process.

B. *Die Forging*

From the theoretical calculation and combined with the simulation results, a set of precision cold stamping dies for the straight bevel gears have been designed (Figure 10). The punch and die are designed with the suitable material and structure to ensure the life of the mold; the bottom of the die has a product push pin design, which helps to remove the stamping details from the inside of the die, the punch pads, and the die cushion. The backplate of the punch and die is designed to prevent the punch from sinking into the die base.

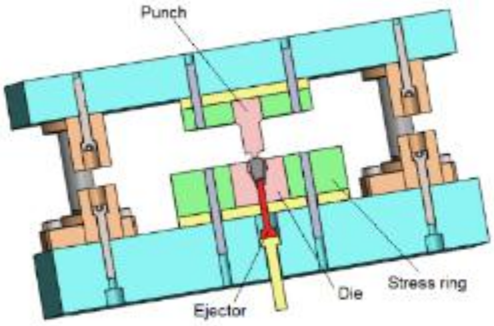
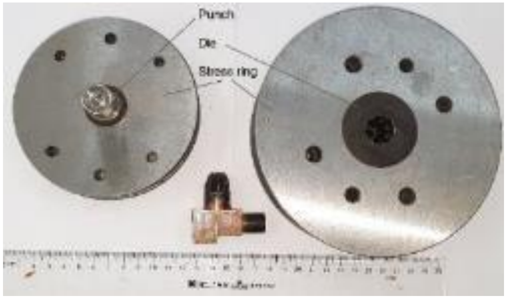


Figure 10. Assembly of Die Set



a) Punch (left) and die (right) used for experiments

b) Assembled dies

C. *Experimental results*

The experimental set of cold forging bevel gears is manufactured according to the calculations and designs above:

To determine the stamping force in the forming process, a measuring system has been designed and manufactured:

Fig. 12. System of measuring force/stroke

The test stamping results on the designed and manufactured system show that, with the right size of workpiece, the product after cold forging meets the specified technical requirements, without defects:

Fig. 13. Experimental forging of bevel gears in closed die

According to the theoretical calculation, the maximum stamping force measured during the experiment is 17.2 tons, according to the theoretical calculation is 17.8 tons, through simulation, the maximum number of stamping forces is determined to be 16.5 tons. Theoretical calculation, simulation, and experimental forces have a small deviation with a maximum deviation from the theoretical calculation of 7.3%.

IV. CONCLUSION

In this study, the mold design process for cold stamping of straight bevel gears is analyzed by numerical simulation technology. Simulation also allows to study material flow, effective strain, effective stress, breaking capacity, stamping force in order to evaluate the possibility of scrap and optimize the design. Based on the verified process from FE simulations, the die set is optimally designed and manufactured for the precision cold stamping process verification test.

The straight bevel gear has been successfully fabricated by hot and cold precision forging processes. The results showed a close agreement between the numerical simulation and experimental analysis of straight bevel gear. Furthermore, forging technique has some advantages over other traditional methods like saving materials, reducing processing steps, high productivity, good surface finish, and high dimension accuracy. In particular comparing to conventional methods, the forging technique creates products with high mechanical properties due to the uniform and continuous metal flow.

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